Validation of MC predictions for Cherenkov yields of dual readout crystal calorimeters

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Motivation

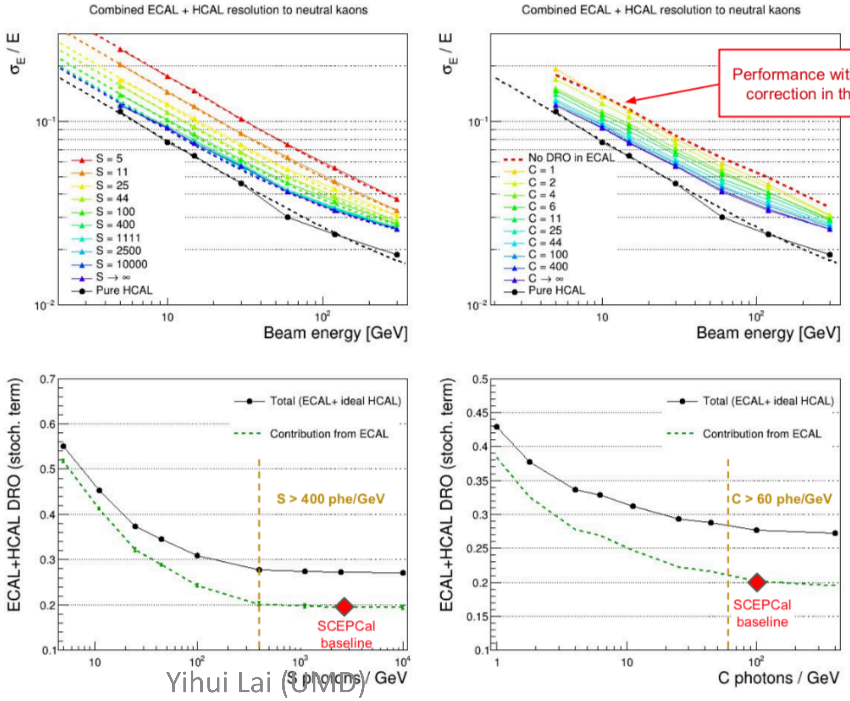
- In order to optimize the dual readout (DRO) detector, a well verified Geant4 ray tracing simulation tool is needed
- The number of detected photons will directly affect the stochastic term of resolution

Slide borrowed from Marco Lucchini

Photo-statistic requirements for S and C

Smearing according to Poisson statistics

- Poor S directly impact the ECAL resolution stochastic term (even without DRO):
  - S > 400 phe/GeV to limit the contribution to HCAL stoch. term below 20%
- A limited resolution to C (photostatistics) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV to limit the contribution to HCAL stoch. term below 20%



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N. Akchurin, et al. https://www.sciencedirect.com/science/article/pii/S0168900212014520

Geometry and material description in the paper

- 7 $PbWO_4$ crystals with dimensions of $30 \times 30 \times 200\ mm^3$
- All crystals were individually wrapped with aluminized mylar sheet
- Hamamatsu R8900 PMT used
- Both the upstream and downstream end faces of the matrix were covered with a large optical transmission filter (U330 or UG5)
- Silicone cookies were used to reduce the light trapping effect

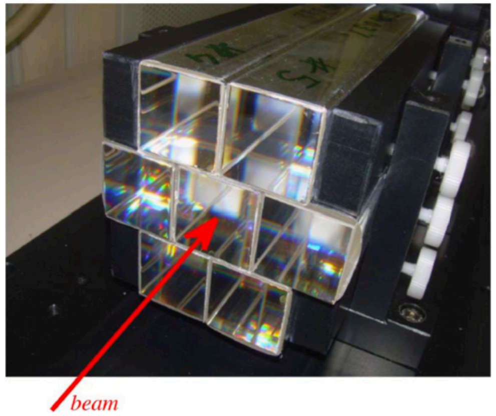
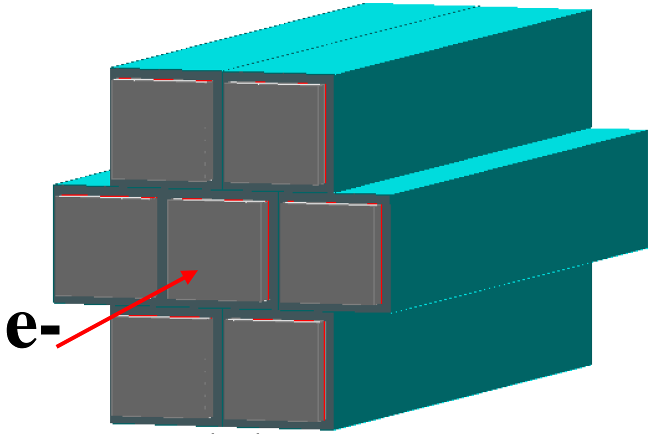
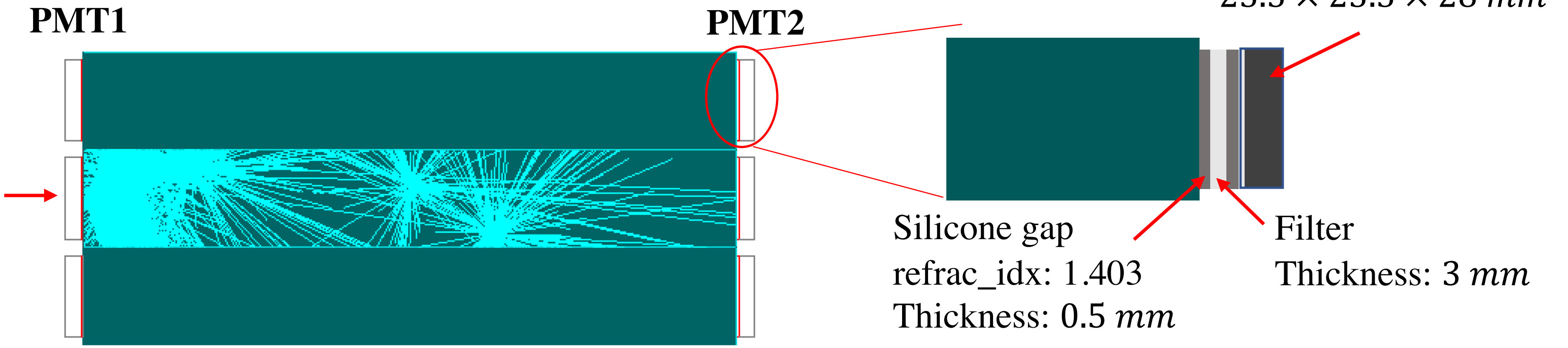


Fig. 2. The PWO matrix consisted of seven crystals with dimensions of $3 \times 3 \times 20\ cm^3$. These were arranged as shown in the figure and the beam entered the matrix in the central crystal. All crystals were individually wrapped in aluminized mylar. Both the upstream and downstream end faces were covered with filters. See text for details.

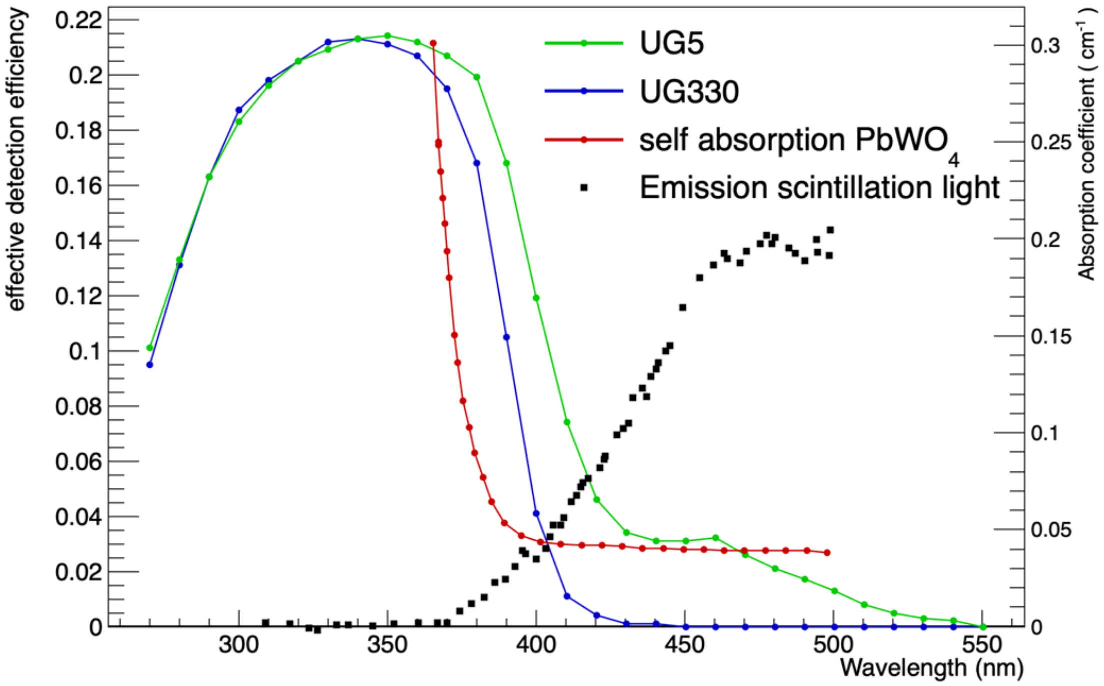
GEANT4 geometry

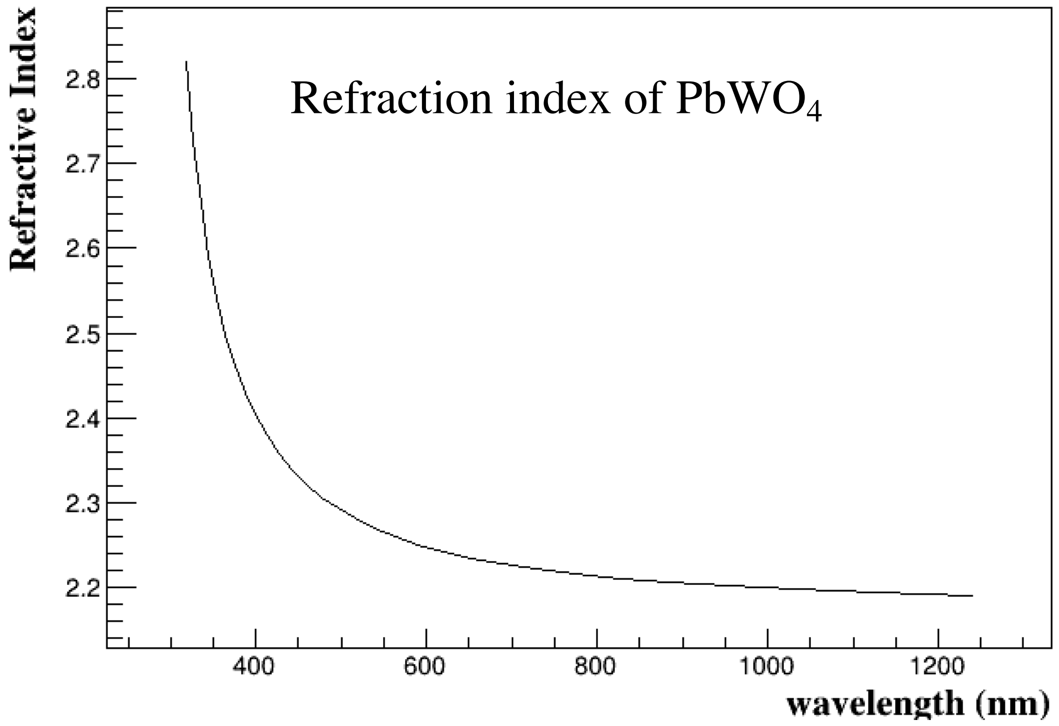




Other parameters used in simulation

- The effective detection efficiency = filter transmission × PMT photon detection efficiency (applied at the last step of simulation)
- In Geant4 optical simulation, Cherenkov photons are only generated in physical volume with well defined refraction. The right-side plot shows the refractive index of $PbWO_4$
- Github repository: https://github.com/yihui-lai/cepc_dual. Based on Marco Lucchini's code

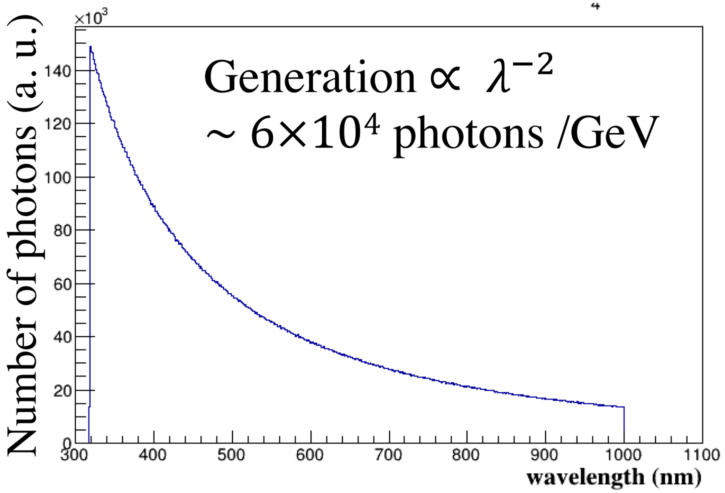




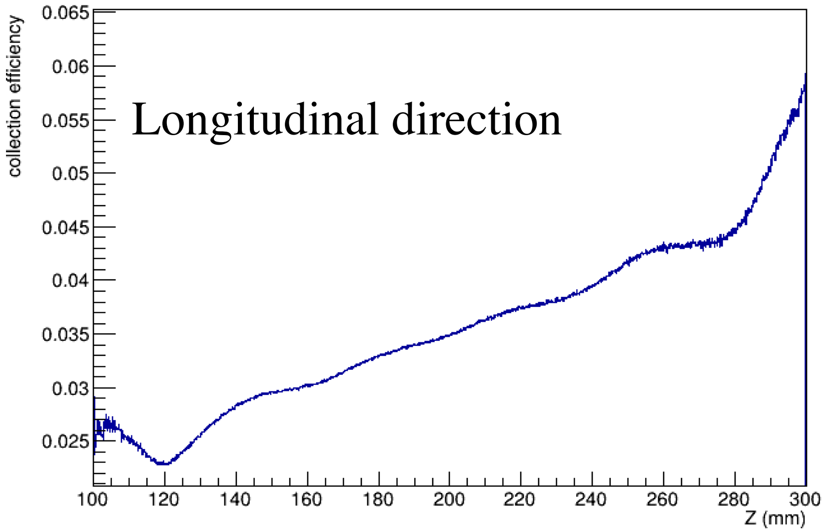
Thanks to G. Gaudio for help in retrieving details of the setup!

Simulation – Cherenkov light

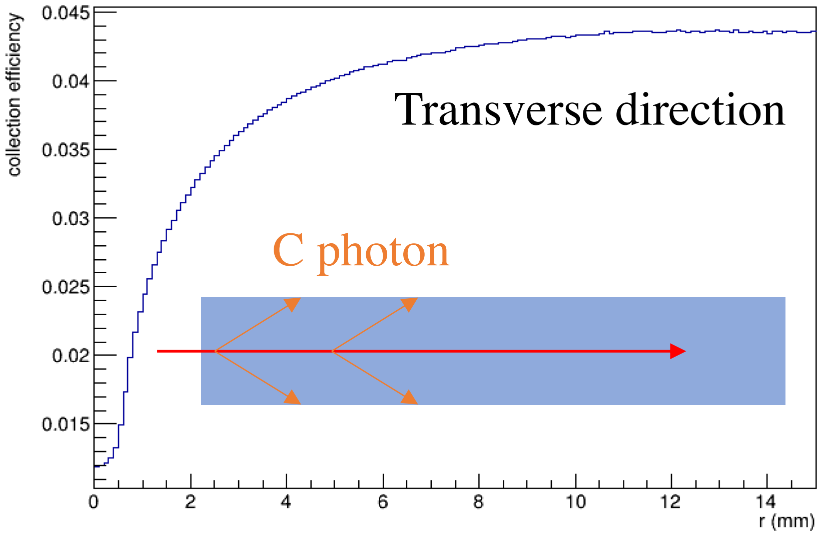
- Generation:
  Cherenkov light is produced proportional to the inverse wavelength squared
- Propagation:
  Only optical photons with wavelength in 300 – 1000 nm are considered for tracking
  Optical photons are traced through the crystal until they reach the photodetector
- Detection:
  Effective detection efficiency in previous slide is applied
  The wavelength distribution of detected photons are shown below



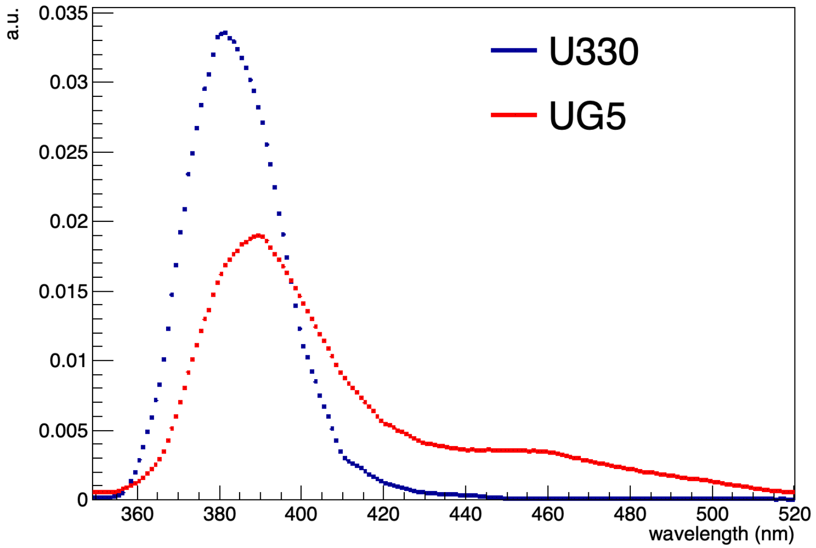
Geometric light collection efficiency (LCE)



PMT1 PMT2



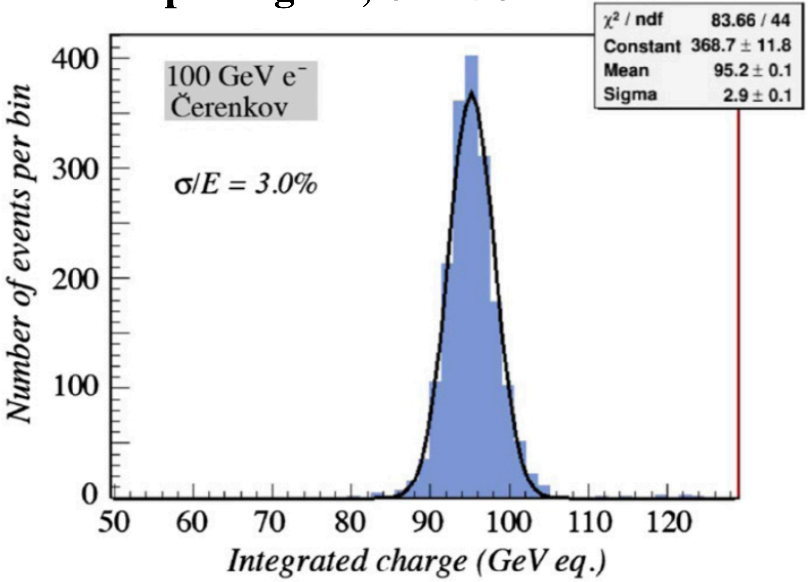
Cherenkov photons detection



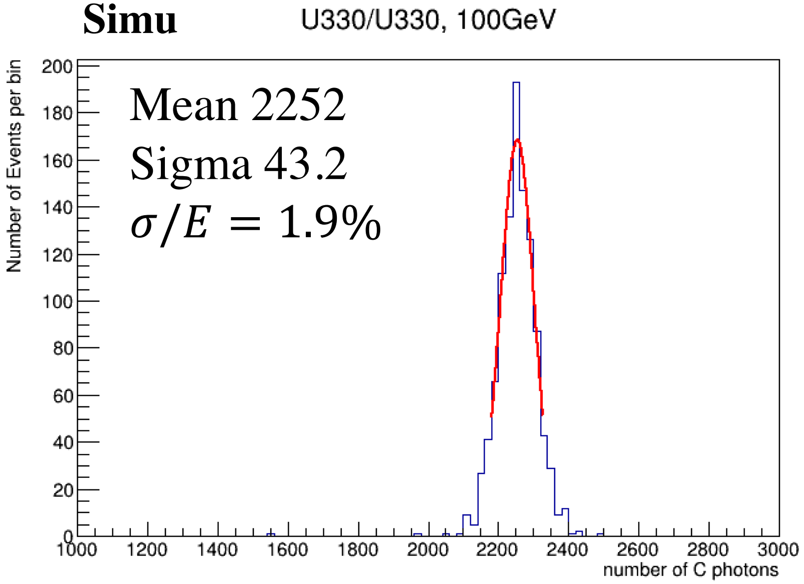
Simulation/data comparison

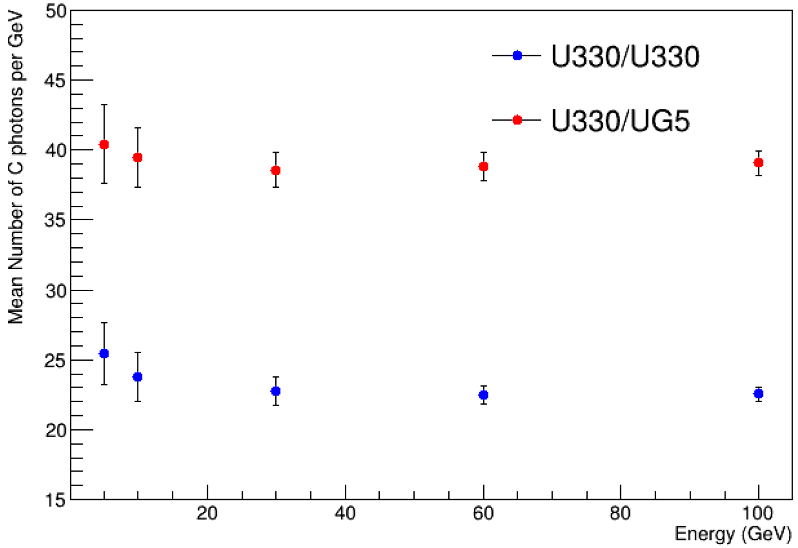
- Cherenkov photons detected on both ends are summed (to reduce the signal nonlinearity)
- 2 filter combinations are simulated, U330/U330 and U330/UG5 (PMT1/PMT2)
- The number of detected Cherenkov photons is not shown in the paper, but it is derived from the resolution plot
- From simulation, the average light yield is **23/GeV** for U330/U330 and **39/GeV** for U330/UG5

Paper Fig. 13, U330/U330



Simu

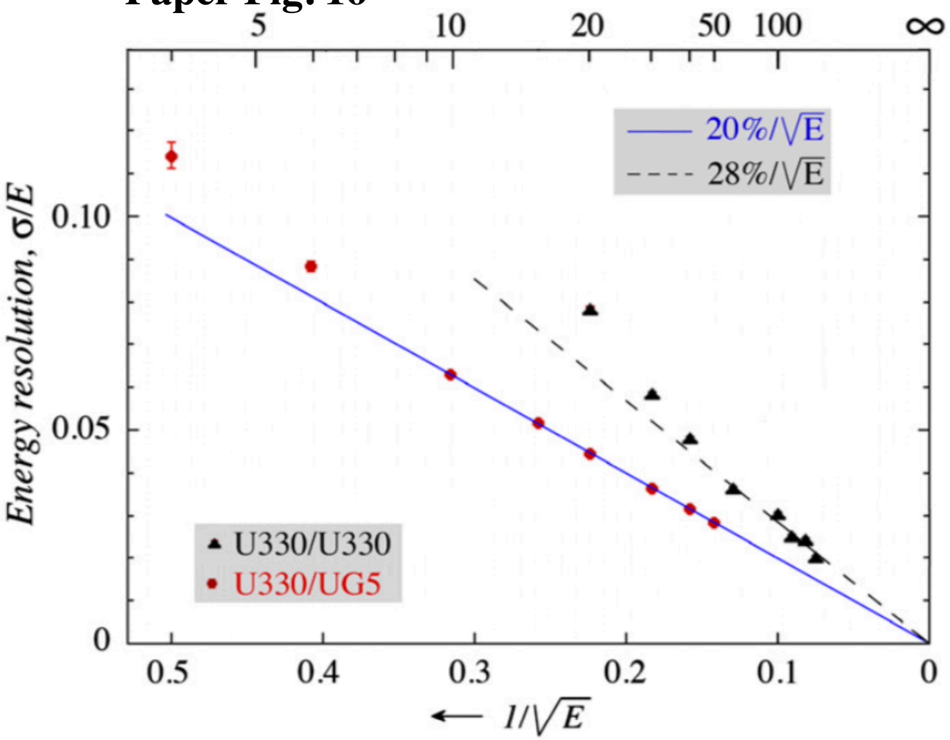




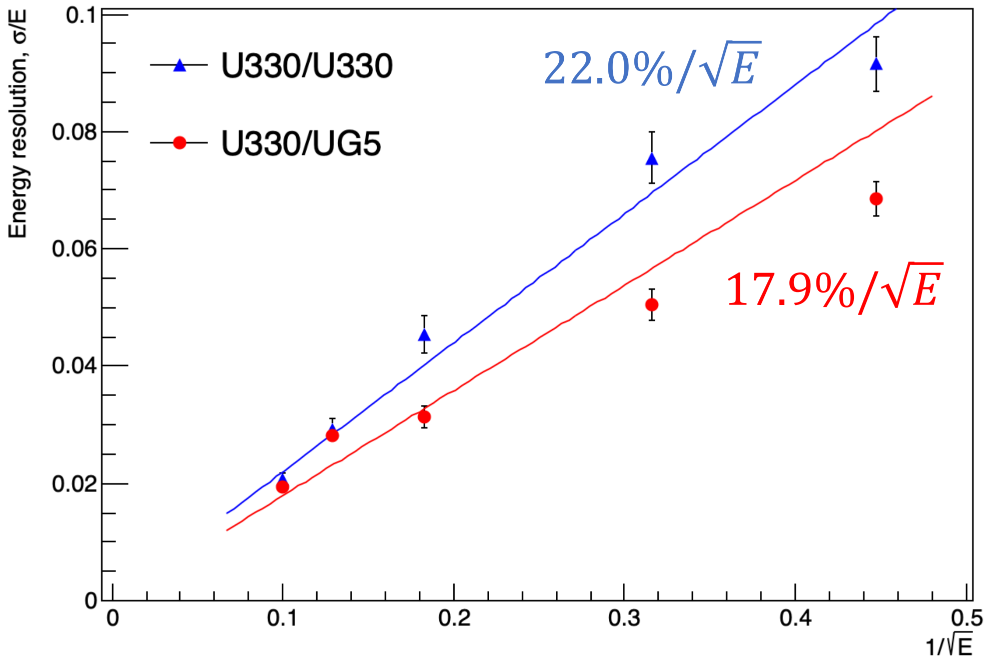
Simulation/data comparison

- In experiment: The energy resolution plot is well described by a straight line. The stochastic fluctuations dominate the energy resolution.
- Assuming these fluctuations are entirely determined by photoelectron statistics, $N = \frac{1}{a^2_{stoch.\,term}}$. The light yield is **13/GeV** for U330/U330 and **25/GeV** for U330/UG5
- In simulation: following the same method, the light yield is **21/GeV** for U330/U330 and **31/GeV** for U330/UG5

Paper Fig. 16



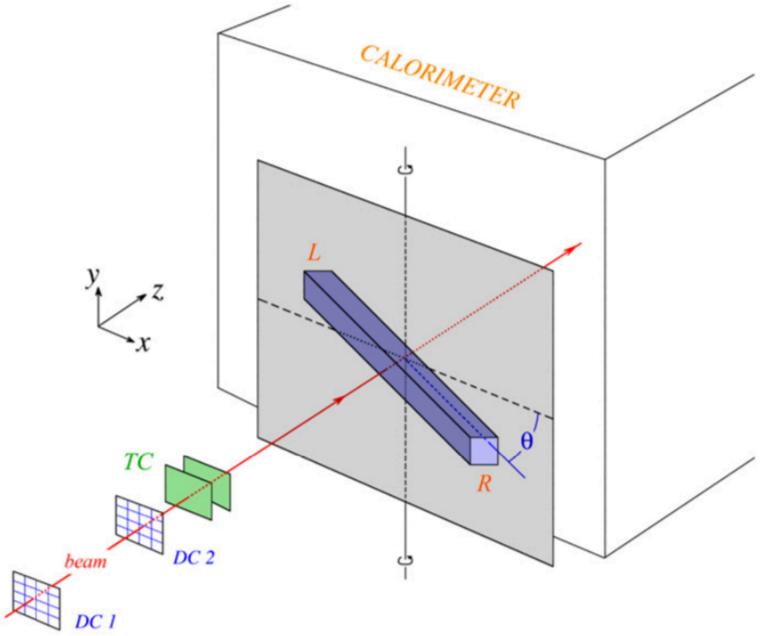
Simu

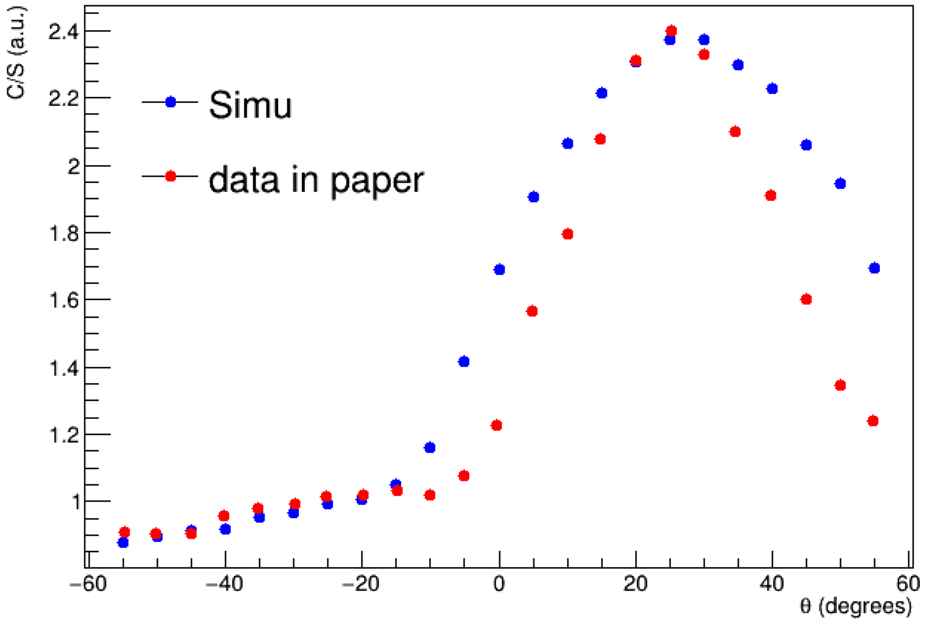


Angular dependence of Cherenkov detection

N. Akchurin, et al. https://www.sciencedirect.com/science/article/pii/S0168900210011885

- One crystal with dimension of $20 \times 20 \times 200\ mm^3$
- The crystal was mounted on a platform that could rotate around a vertical axis
- U330 filter mounted on the R side (Cherenkov, "C"), GG495 filter on the L side (transmit only light > 495nm, Scintillation, "S")
- With tuned misidentification ratio, the angular dependence of C/S ratio is shown below, $r_{s\_leak} = 0.11, r_{c\_leak} = 0.2$





$$N_R = C_R + S_R * r_{s\_leak}$$

$$N_L = S_L + C_L * r_{c\_leak}$$

- Signals in R side are considered as C photons, but it is possible that S photons also pass the U330 filter and misidentified as C

Still work with Gabriella Gaudio to get the number of photons vs. angle

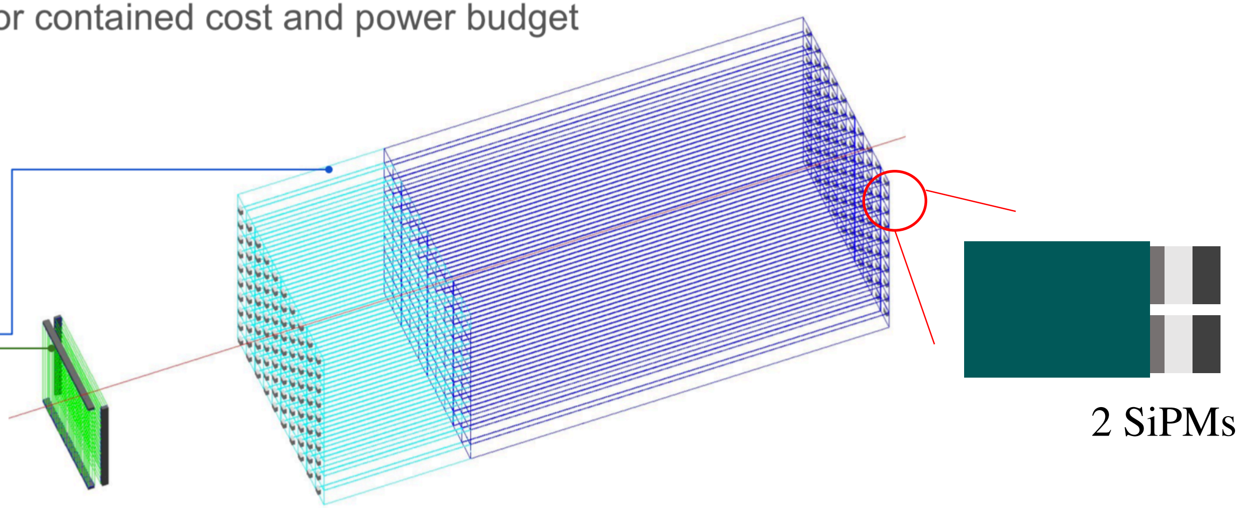
The optimization of SCEPCal

- Use the tool to calculate of expected LCE for different crystal and SiPM dimensions
- Only the rear segment of SCEPCal is DRO
- 2 SiPMs are used at the same downstream end
- Reflective sheet is inserted between front and rear segment to increase the LCE

Slide borrowed from M. Lucchini

- ***SCEPCAL:*** a **S**egmented **C**rystal **E**lectromagnetic **P**recision **C**alorimeter
- **Transverse and longitudinal segmentations** optimized for particle identification, shower separation and performance/cost
- Exploiting **SiPM readout** for contained cost and power budget

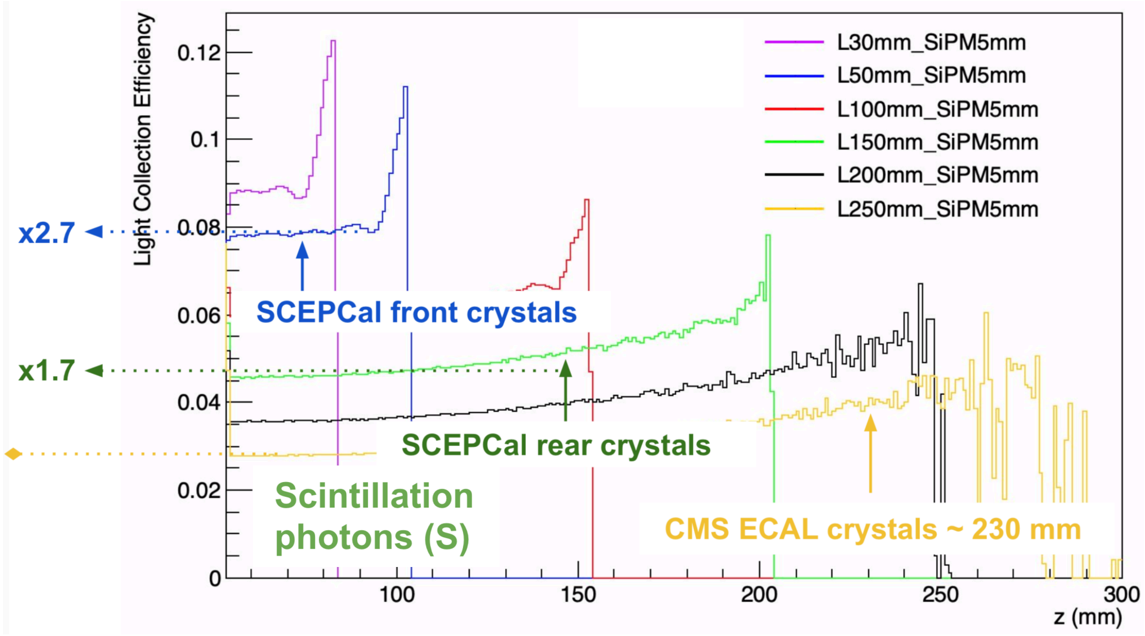
- **Timing layer** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layer** — $\sigma_E/E \sim 3\%/\sqrt{E}$
  - PbWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)

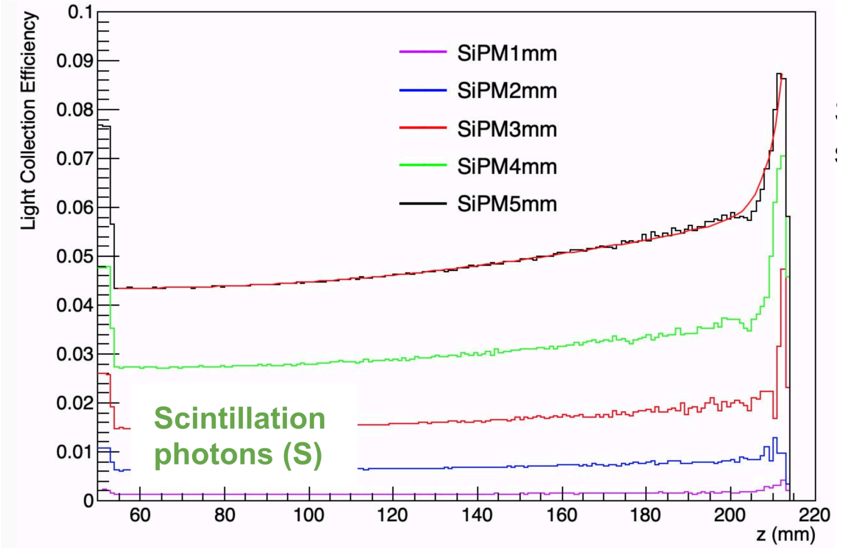


2 SiPMs

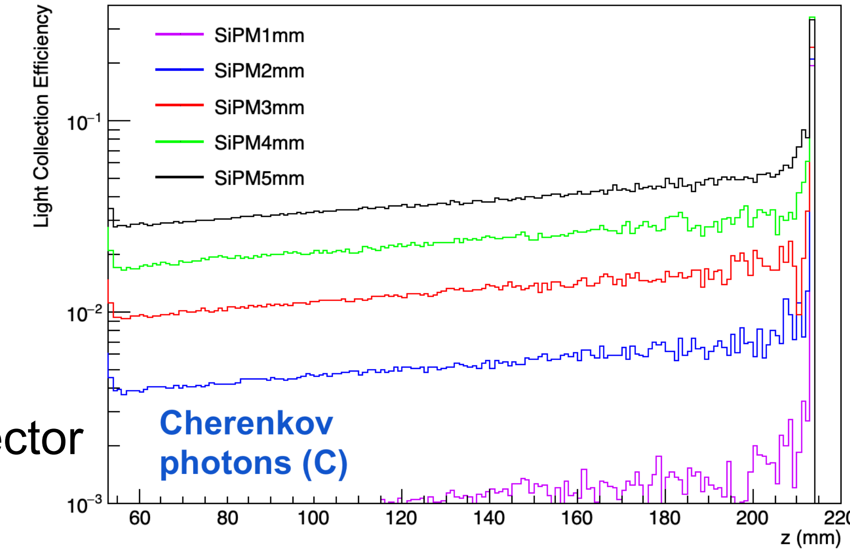
The optimization of SCEPCal

- LCE for rear SCEPCal crystal
  - LCE grows linearly with SiPM active area
  - LCE grows with shorter crystals





reflector side

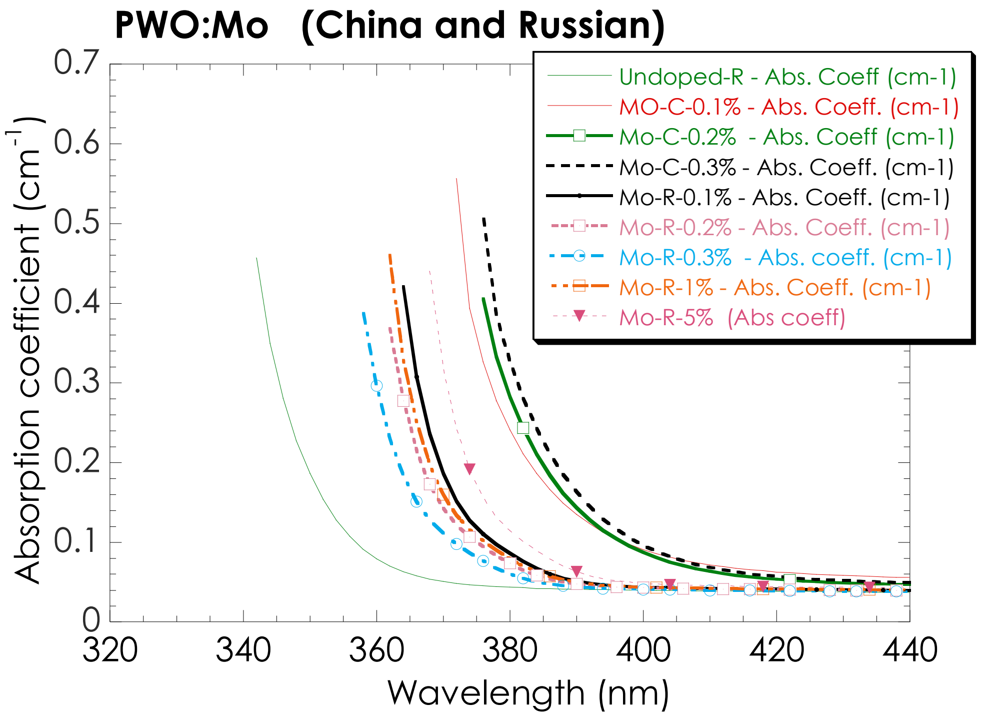


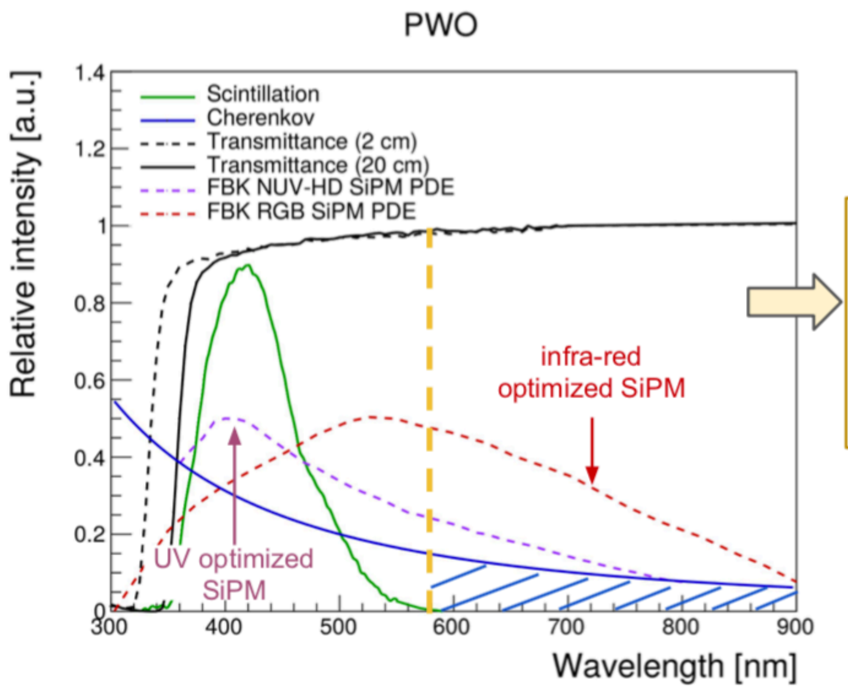
SiPM side

Conclusion

- The MC simulation predicts ~ 1.5 times Cherenkov photons
- Given not including many details such as the misidentification, It is possible to see some disagreement
- Overall, the simulation on Cherenkov light using GEANT4 is close enough to the data to support studies of the optimization of SCEPCal

Backup



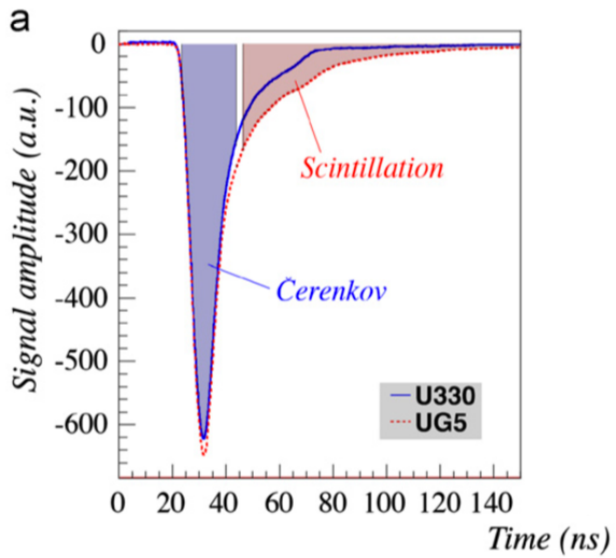


Cherenkov photons above scintillation peak are much less affected by self-absorption

Possible correction

How the scintillation light and Cherenkov light are distinguished in the paper?

- Light collected in a time window of 20 ns around the peak is considered Cherenkov light, light collected more than 15 ns beyond the peak is considered scintillation light.



- Consider the contamination from scintillation light, the Cherenkov signals are calculated as below

let N_{CT} be the true number of cerenkov photoelectrons (PEs) in the blue (cerenkov) region
let N_{S1} be the true number of scintillation PEs in the blue region
let N_{S2} be the true number of scintillation PEs in the red (scintillation) region
Assume the number of cereknov PEs in the red region is negl.
Then the estimated number of cerenkov PEs N_{CE} is:

$$N_{CE} = N_{CT} + N_{S1} - fN_{S2}$$

where f is the average proportionality constant between N_{S1} and N_{S2}

Possible correction

- Error propagation

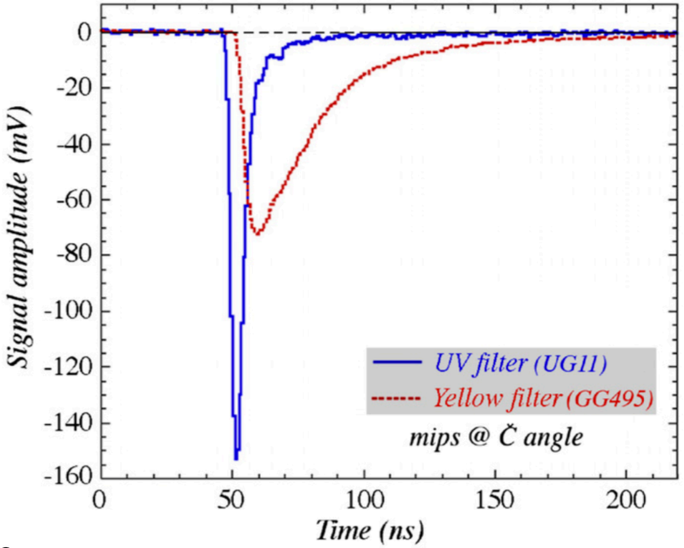
$$N_{CE} = N_{CT} + N_{S1} - fN_{S2}$$

$$\frac{\sigma_E}{E} = \frac{\sqrt{N_{CT} + N_{S1} + f^2 N_{S2}}}{N_{CT} + N_{S1} - fN_{S2}}$$

$$\frac{\sigma_E}{E} = \frac{\sqrt{N_{CT} + fN_{S2} + f^2 N_{S2}}}{N_{CT}}$$

- Assume $N_{S2} = cN_{CT}$, an estimation of the average time structure of signals at the right side tells me $f \approx 0.28, c \approx 1.35$

$$\frac{\sigma_E}{E} = \frac{\sqrt{1 + fc(1+f)}}{\sqrt{N_{CT}}} = \frac{1.22}{\sqrt{N_{CT}}}$$



- the resolution plot in the paper shows Cherenkov yield of U330/U330 is $0.28/\sqrt{E}$, of U330/UG5 is $0.2/\sqrt{E}$. Corresponding to number of photons 19/GeV and 37.5/GeV

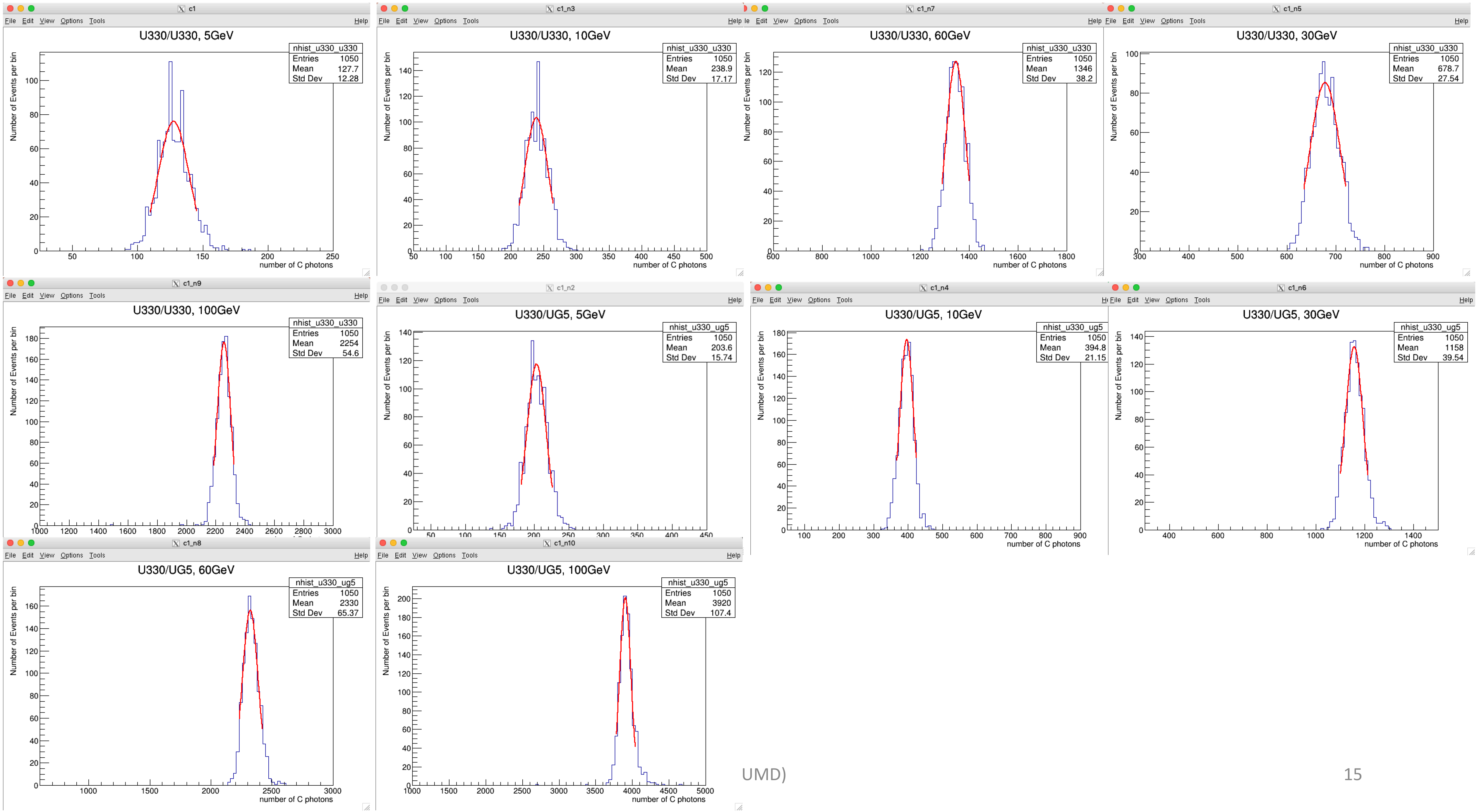
$$\frac{r}{\sqrt{E}} = \frac{1.22}{\sqrt{N_{CT}}}$$

↓

$$\frac{N_{CT}}{E} = \frac{1.5}{r^2}$$

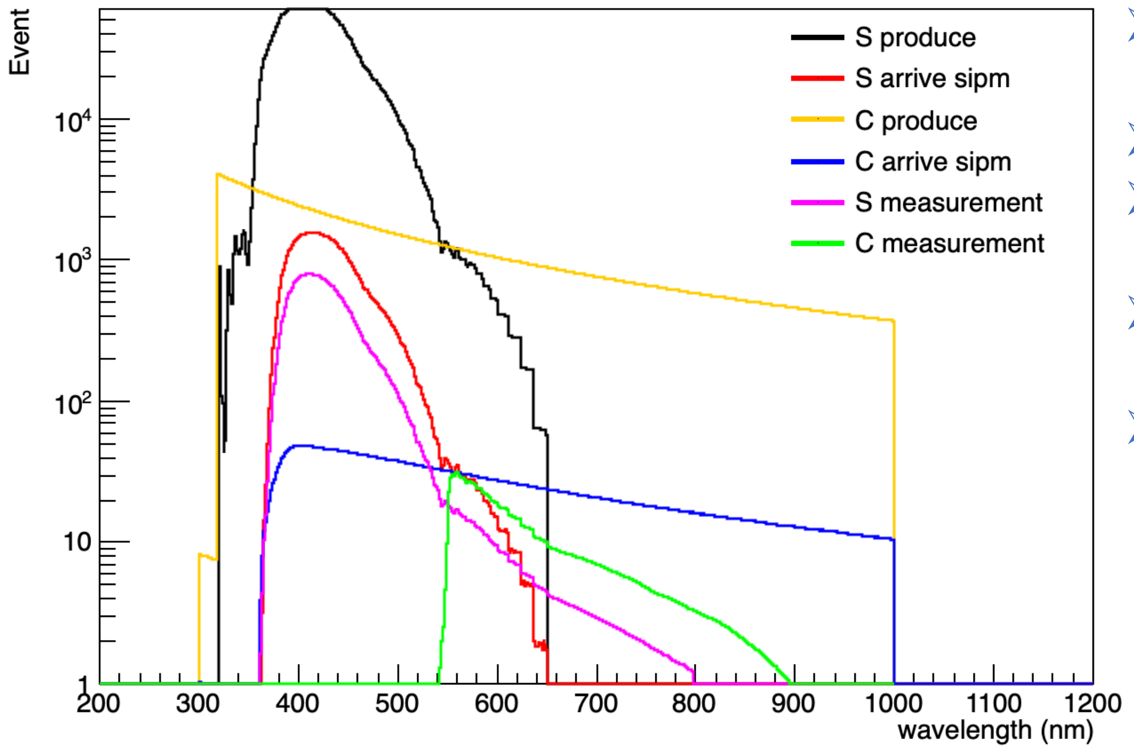
Filters	Before correction	After correction
U330/U330	13/GeV	19/GeV
U330/UG5	25/GeV	37.5/GeV

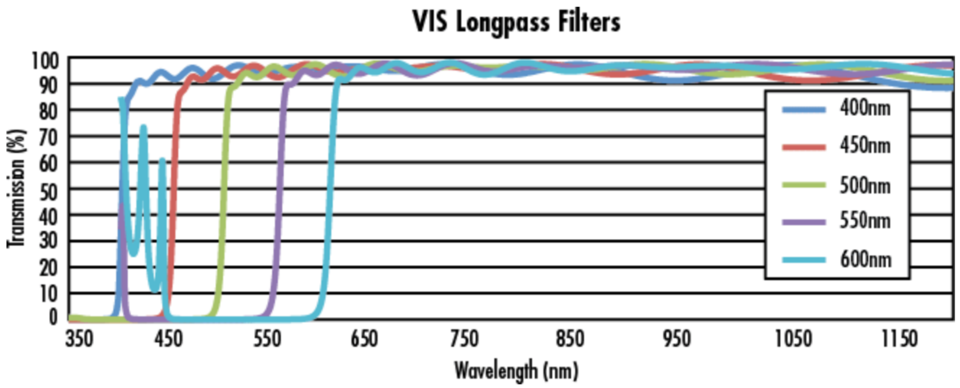
- Caveat: this is only a rough estimation since the filter used in above waveforms is much stricter


U330/U330, 5GeV
nhist_u330_u330
Entries 1050
Mean 127.7
Std Dev 12.28
U330/U330, 10GeV
nhist_u330_u330
Entries 1050
Mean 238.9
Std Dev 17.17
U330/U330, 60GeV
nhist_u330_u330
Entries 1050
Mean 1346
Std Dev 38.2
U330/U330, 30GeV
nhist_u330_u330
Entries 1050
Mean 678.7
Std Dev 27.54
U330/U330, 100GeV
nhist_u330_u330
Entries 1050
Mean 2254
Std Dev 54.6
U330/UG5, 5GeV
nhist_u330_ug5
Entries 1050
Mean 203.6
Std Dev 15.74
U330/UG5, 10GeV
nhist_u330_ug5
Entries 1050
Mean 394.8
Std Dev 21.15
U330/UG5, 30GeV
nhist_u330_ug5
Entries 1050
Mean 1158
Std Dev 39.54
U330/UG5, 60GeV
nhist_u330_ug5
Entries 1050
Mean 2330
Std Dev 65.37
U330/UG5, 100GeV
nhist_u330_ug5
Entries 1050
Mean 3920
Std Dev 107.4
Number of Events per bin
number of C photons

UMD)

Light collection of SCEPCal





- RGB and UV SiPM are used to detect Cherenkov and scintillation photons
- All the photons detected by UV SiPM are considered as S
- The 550nm filter is added to RGB SiPM, so only photons with wavelength > 550nm could be detected. In this region, C is dominant
- The left plot shows spectrum of S and C when they are produced, arrived at SiPM and detected
- The number of photons at different stages are shown in the table below, but it is a rough estimate, as the scintillation spectrum I am using is clearly rough up when wavelengths > 550nm.

	S	C
Generate	4.5×10^5/GeV	5.655×10^4/GeV
Arrive at the End	5%	3.8%
Detected by SiPM	UV (1.1%) RGB (0.014%)	UV (0.49%) RGB (0.28%)

Misidentification as C